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Yanxi Lu
University of Illinois at Urbana-Champaign

Morgan D. Hayes
University of Kentucky, hayesmorgan@uky.edu

John P. Stinn
Iowa Select Farms

Tami M. Brown-Brandl
USDA Agricultural Research Service

Hongwei Xin
Iowa State University

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EVALUATING VENTILATION RATES BASED ON NEW HEAT AND MOISTURE PRODUCTION DATA FOR SWINE PRODUCTION

Y. Lu, M. Hayes, J. Stinn, T. Brown-Brandl, H. Xin

ABSTRACT. *Heat and moisture production (HMP) rates of animals are used for calculation of ventilation rate (VR) in animal housing. New swine HMP data revealed considerable differences from previously reported data. This project determined new design VRs and evaluated differences from previously recommended VRs. The swine production stages evaluated included gestation, farrowing, nursery, growing, and finishing. The ranges of ambient temperature and ambient relative humidity (RH) evaluated for VR were -25°C to 15°C in 10°C increments and 15% to 75% in 15% increments, respectively. Indoor set points for temperature and RH were, respectively, 15°C, 20°C, 25°C and 60%, 70%, 80% for all five ambient stages. The results showed that the old VR for moisture control was 54%, 30%, 69%, 31%, and 53% lower than the new VR for the gestation, farrowing, nursery, growing, and finishing stages, respectively. Updated recommendations for ventilation are necessary for designing and managing modern swine facilities.*

Keywords. *Building design, Heat production, Moisture production, Swine, Ventilation rate.*

For the past 60 years, pigs have been predominantly raised indoors for better food safety, management, and performance (Brown-Brandl et al., 2004). It is critical to have adequate control of temperature and humidity for animals raised in barns to maintain high levels of animal well-being and productivity (Zhang, 1994). Total heat production (THP) can be partitioned into sensible heat production (SHP) and latent heat production (LHP) or moisture production (MP). Animal-level sensible heat is lost mainly from the animal's body, while latent heat is dissipated through the animal's breathing and by evaporation from its skin (Zhang, 1994). Rates of SHP and MP from animals and their environmental conditions are important in swine housing design because they can be used for calculation of design ventilation rate (VR). Most of the design VRs for swine housing have been based on SHP and MP rates from studies conducted in the 1950s and 1970s (Stinn and Xin, 2014). Because genetics, nutrition/feeding, and production methods have changed since then (Brown-Brandl et al., 2004), SHP and MP for both swine and their modern facilities have also changed, and design VRs are expected to be different from previously recommended VRs. An ideal ventilation system should reduce the potential for heat stress during hot weather and remove excessive moisture from barns in the winter. During cold weather, underventilation results in high relative humidity (RH), which adversely affects air quality and is favorable for the growth of disease microorganisms. In addition, higher RH leads to excessive moisture buildup and condensation on the walls during cold weather, which prematurely degrades the structural integrity. In contrast, overventilation contributes to a dusty environment, which results in respiratory concerns for the animals and requires excessive fuel for supplemental heating (Brown-Brandl et al., 2014).

Chepete and Xin (2004) completed a similar study to update VRs for laying hens. Newly collected data showed that SHP and MP were 8% lower and 22% higher than the old bird-level values, which had been the basis for evaluating the design and operation of laying-hen house ventilation systems. VRs based on old SHP and MP values were 10% higher and 18% lower, respectively, for temperature and moisture control than the new VRs. The study closely evaluated how balance temperature was influenced by indoor temperature and RH set points (Chepete and Xin, 2004).

Similarly, higher SHP and MP values have recently been published for swine production. Brown-Brandl et al. (2014) provided recently collected heat moisture production (HMP) data for all stages of modern swine production. HMP at both calorimeter level and facility level were studied. HMP of swine were compared among different stages, including nursery piglets, growing pigs, early finishing pigs, late finishing pigs, gestating gilts, and farrowing sows. Calorimeter-level THP and LHP were described by equations based on ambient temperature and animal weight. The results indicated that the facility-level THP agreed with the calorimeter data except for the nursery piglets, but LHP values at the calorimeter level were less than those observed at the facility

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The authors are **Yanxi Lu, ASABE Member,** Graduate Student, Department of Agricultural and Biological Engineering, University of Illinois, Urbana, Illinois; **Morgan Hayes, ASABE Member,** Assistant Professor, Department of Biosystems and Agricultural Engineering, University of Kentucky, Lexington, Kentucky; **John P. Stinn, ASABE Member,** Environmental Projects Manager, Iowa Select Farms, Iowa Falls, Iowa; **Tami Brown-Brandl, ASABE Member,** Agricultural Engineer, USDA-ARS Meat Animal Research Center, Clay Center, Nebraska; **Hongwei Xin, ASABE Fellow,** Distinguished and Endowed Professor, Department of Agricultural and Biosystems Engineering and Animal Science, and Director, Egg Industry Center, Iowa State University, Ames, Iowa. **Corresponding author:** Morgan Hayes, 212 C.E. Barnhart Bldg., University of Kentucky, Lexington, KY 40546; phone: 859-218-4350; e-mail: hayesmorgan@uky.edu.

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level. THP of modern pigs is higher than the current standards except for the nursery stage. Updated THP and MP values were recommended by the authors to design VRs for current swine facilities. Stinn and Xin (2014) studied facility-level THP and MP rates of modern U.S. breeding swine in gestation and farrowing. Compared with old data from ASABE Standard EP270.5 (ASABE, 2012), THP, LHP, and SHP were 35%, 72%, and 19% higher than the old values for the early gestation stage and 12%, 34%, and 3% higher than the old values for late gestation. Values for the farrowing stage showed increases of 29%, 52%, and 6% in THP, LHP, and SHP compared to ASABE Standard EP270.5 (ASABE, 2012). Updating of the standards used in the design and operation of ventilation systems for swine barn was also recommended (Stinn and Xin, 2014).

With the differences in HMP noted above and similar VR evaluations for other species based on new HMP data, the expectation is that the recommended VRs for swine housing would increase appreciably. Therefore, the overall goal of this study was to provide specific VR guidelines based on various indoor and outdoor conditions. The specific objectives were to determine new swine VRs based on new HMP values and to compare the new VR values to the previously published recommendations.

Materials and Methods

Facility Description

In order to determine ventilation requirements, assumptions about the facilities were made to account for heat transfer through the building envelope. Building dimensions and capacities for farrowing, gestation, and wean-to-finish barns are described below. The facilities descriptions came from research completed on commercial sites. All VR scenarios were run with the assumption that the barns were at full capacity.

The farrowing site assumptions were based on Stinn and Xin (2014), who provided a schematic of a farrowing facility. The farrowing site was assumed to be a barn with nine farrowing rooms. The farrowing rooms each had dimensions of 15.5 m × 13.9 m with a shallow (0.61 m deep) manure pit. Each farrowing room had 40 farrowing crates. A 125 m hallway with an evaporative pad (73.2 m × 1.2 m) provided a shared inlet for the nine rooms. Each room was equipped with two 0.3 m diameter pits fans, two 0.6 m diameter variable-speed fans, one 0.91 m diameter fan, and one 1.2 m diameter fan to provide ventilation (Stinn and Xin, 2014). The capacity of the farrowing barn was assumed to be 360 sows with litters for all nine rooms (Stinn and Xin, 2014).

The gestation site assumptions were also based on Stinn and Xin (2014), who also provided a schematic of a gestation facility. The gestation barn was assumed to be 121.9 m × 30.5 m with mechanical ventilation year round and a capacity of 1800 gestation sows. The barn had a total of twelve 0.61 m diameter pit fans, six each on the south and north sides, and fifteen 1.37 m diameter tunnel fans on the west endwalls. Evaporative cooling pads were installed on the east endwall and on the middle section of each sidewall for summer cooling (Stinn and Xin, 2014).

The nursery, growing, and finishing stages were accommodated with one wean-to-finish barn, which was double-stocked except during the finishing stage. A detailed description of the facility is provided by Pepple (2011). The barn had dimensions of 25 m × 57 m with a deep-pit manure storage and a capacity of 2400 pigs (single-stocked). The barn had eight 0.6 m diameter pit fans and four 0.6 m diameter endwall fans providing the minimum ventilation. Sidewall curtains on both the north and south walls of the barn were used to provide natural ventilation during the summer (Pepple, 2011).

The sidewalls for all barns mentioned above were assumed to be concrete block and stud wall with insulation, which is typical for housing large swine (Jones and Friday, 1995).

Data Source for VR Calculation

All heat production rates used in both recent studies (Brown-Brandl et al., 2014; Stinn and Xin, 2014) and the previously reported ASABE Standard EP270.5 (ASABE, 2012) are listed in table 1. Typical THP and SHP values for the nursery, growing, and finishing stages were from calorimeter equations, while LHP values were from facility-level measurements (Brown-Brandl et al., 2014). LHP or MP at the facility level instead of the animal level was used in this study because MP from unvented heaters, water wastage, sprinkle-cooling systems, and waste-handling systems is a significant contribution in empty barns (Brown-Brandl et al., 2014). Accounting for this facility-level MP would lead to an increase in the recommended minimum ventilation, and it was therefore included. Values for the gestation and farrowing stages were from Stinn and Xin (2014). These values for THP, SHP, and LHP were all measured at facility level. The contribution of solar gain and the heat from typically fluorescent lights were ignored; hence, animal heat was considered the only sensible heat source (Chepete and Xin, 2004).

For the VR calculations, a range of environmental conditions was used to demonstrate how indoor and outdoor conditions affect the required VR. The range of ambient temperature was -25°C to 15°C in 5°C increments, and the range of ambient RH was 15% to 75% in 15% increments. Indoor temperature set points were 15°C, 20°C, and 25°C, while indoor RH set points were 60%, 70%, and 80%. The outdoor

Table 1. Summary of updated THP, SHP, and MP values for swine at different production stages: "Study" is new HMP data and "ASABE" (ASABE, 2012) is old HMP data.

	Gestation		Farrowing		Nursery		Growing		Finishing	
	Study	ASABE	Study	ASABE	Study	ASABE	Study	ASABE	Study	ASABE
Mass (kg)	204	200	175	177	16.7	17.5	34.0	40.0	117	100
THP (W kg^{-1})	1.86	1.40	3.28	2.60	4.83	5.00	4.04	3.10	2.07	1.90
SHP (W kg^{-1})	0.95	0.97	1.66	1.30	2.85	3.50	2.29	1.60	1.27	1.10
LHP (W kg^{-1})	0.91	0.43	1.62	1.30	5.35	1.50	1.94	1.50	0.82	0.80
MP (g h^{-1} kg^{-1})	1.34	0.70	2.38	1.80	7.86	2.20	2.85	2.20	1.20	1.20

settings cover the temperature and RH conditions for many regions with cold to moderate temperatures.

Ventilation Rate for Moisture Control

The method of determining minimum VR for moisture control from Chepete and Xin (2004) and Albright (1990) was applied. Minimum VR was calculated as:

$$V_{H_2O} = \frac{MP \times M}{\rho \times (W_i - W_o) \times 1000} \quad (1)$$

where V_{H_2O} is VR for moisture control (m^3 h^{-1}), M is mass (kg), MP is moisture production (g h^{-1} kg^{-1}), ρ is density of air (kg m^{-3}) based on outside temperature and is the inverse of specific volume, and W_i and W_o are inside and outside humidity ratio (kg H_2O kg^{-1} dry air), respectively.

$$V_{moistair} = \frac{\frac{1}{P_a} \times R_a \times t_{db} \times (1 + 1.6078W)}{1 + W} \quad (2)$$

where $V_{moistair}$ is specific volume of moist air (m^3 kg^{-1}), P_a is barometric pressure of the inside or outside air (Pa), R_a is dry air gas constant (287.055 J kg^{-1} K^{-1}), t_{db} is absolute dry bulb temperature (°C), and W is humidity ratio for indoor or outdoor air of the following form:

$$W = 0.62198\left(\frac{P_w}{P_a - P_w}\right) \quad (3)$$

where P_w is partial vapor pressure of the indoor or outdoor air of the following form:

$$P_w = \text{RH} \times P_{ws} \quad (4)$$

where RH is indoor or outdoor relative humidity, and P_{ws} is saturation vapor pressure of inlet or outlet air of the following form:

$$P_{ws}(t) = e^{\left[\frac{C_1}{t} + C_2 + C_3 \times t + C_4 \times t^2 + C_5 \times t^3 + C_6 \times t^4 + C_7 \times \ln(t)\right]} \quad (5)$$

For -100°C ≤ t < 0°C, the coefficients are:
C_1 = -5.6745359 × 10^3, C_2 = 6.3925247,
C_3 = -9.677843 × 10^{-3}, C_4 = 6.22157 × 10^{-7},
C_5 = 2.0747825 × 10^{-9}, C_6 = -9.484024 × 10^{-13},
and C_7 = 4.1635019.
For 0°C ≤ t ≤ 200°C, the coefficients are:
C_1 = -5.8002206 × 10^3, C_2 = 1.3914993,
C_3 = -4.8640239 × 10^{-2}, C_4 = 4.1764768 × 10^{-5},
C_5 = -1.4452093 × 10^{-8}, C_6 = 0, and C_7 = 6.5459673.

Ventilation Rate for Temperature Control

The method of determining VR for temperature control as described by Chepete and Xin (2004) and Albright (1990) was applied. Animal heat was considered the only heat source. The structure of the sidewalls for all the studied barns was assumed to be concrete knee walls with insulated studs above. The insulation R-values of the cooling pads, curtains, or fans used in the gestation, farrowing, and wean-to-finish barns were assumed to be negligible. In addition, all buildings were over at least a shallow pit, leading to a negligible perimeter heat loss factor. VR for temperature control was calculated as:

$$V_{temp} = \left[\frac{SHP \times M \times N - (\Sigma UA + FP)(t_i - t_o)}{C_p \times \rho \times (t_i - t_o)} - \frac{(UA)_f (t_i - t_{pit})}{C_p \times \rho \times (t_i - t_o)}\right] \times \frac{3600}{N} \quad (6)$$

where V_{temp} is VR for temperature control (m^3 h^{-1} head^{-1}), N is number of animals, U is thermal conductance of the building component (W m^{-2} °C^{-1}), A is area of the building component (m^2), the ΣUA term includes the constituent components of the wall $(UA)_w$, ceiling $(UA)_c$, and floor $(UA)_f$, FP is perimeter heat loss factor, t_i is inside air temperature (°C), t_o is outside air temperature (°C), C_p is specific heat of air (J kg^{-1} °C^{-1}), and t_{pit} is pit temperature and was assumed to be 5°C lower than indoor temperature (Chepete and Xin, 2004).

Balance Temperature

Balance temperature (t_{bal}) is the temperature at which VR for temperature control equals VR for moisture control and below which supplemental heating is needed to maintain the set point temperature. This value can be determined by plotting V_{temp} and V_{H_2O} based on outside temperature and seeing where the lines intersect; it can also be determined by the following equation:

$$t_{bal} = t_i - \frac{3.6 \times 10^6 \times (W_i - W_o) \times X}{MP \times M \times N \times C_p + 3.6 \times 10^6 \times Y} \quad (7)$$

where $X = SHP \times M \times N + (UA)_f \times (t_i - t_{pit})$

$Y = (W_i - W_o) \times [(UA)_W + (UA)_c]$

Balance temperature can be used to estimate the heating degree days or hours and therefore the total amount of fuel or energy needed to heat a space throughout a typical winter.

Result and Discussion

Tables 2 through 6 list the V_{H_2O} values for moisture control under typical indoor and outdoor conditions by production stages. These tables provide specific V_{H_2O} guidance based on ambient environment and management's set point choices. Overall, increasing indoor RH or temperature (RH$_i$ and t_i) reduces V_{H_2O} at a given outdoor RH and temperature (RH$_o$ and t_o) across all five stages. For instance, as figure 1 shows, increasing t_i from 15°C to 20°C in the gestation stage reduces V_{H_2O} by 37% (at RH$_o$ = 15% and RH$_i$ = 60% across t_o). The line for the 15°C indoor set point shows that higher VR is needed to remove excess moisture as compared with the other two set points. Figure 2 shows that increasing RH$_i$ from 60% to 80% reduces V_{H_2O} by approximately 26% (at t_i = 15°C and RH$_o$ = 15%, growing stage). RH$_o$ has minor effects on V_{H_2O} when compared to RH$_i$. Increasing the RH$_i$ set point results in a drop of t_{bal} due to the decreasing V_{H_2O}. When t_o is below t_{bal}, the t_{bal} can be reduced by increasing the RH$_i$. However, as noted earlier, unmanaged high RH$_i$

Table 2. Moisture control ventilation rates (m^3 h^{-1} head^{-1}) for typical indoor and outdoor conditions for a gestation barn. Average pig weight = 204 kg, MP = 1.34 g h^{-1} kg^{-1}, t_i is indoor temperature setting, t_o is outdoor temperature, RH$_i$ is indoor relative humidity setting, and RH$_o$ is outdoor relative humidity.

		t_i = 15°C			t_i = 20°C			t_i = 25°C		
t_o (°C)	RH$_o$ (%)	60% RH$_i$	70% RH$_i$	80% RH$_i$	60% RH$_i$	70% RH$_i$	80% RH$_i$	60% RH$_i$	70% RH$_i$	80% RH$_i$
-25		30.6	26.1	22.8	22.1	18.9	16.5	16.2	13.9	12.1
-15		32.3	27.5	24.0	23.3	19.9	17.3	17.0	14.5	12.6
-5	15	34.8	29.5	25.6	24.8	21.1	18.3	18.0	15.3	13.3
5		38.9	32.6	28.0	27.2	22.9	19.8	19.4	16.4	14.2
15		46.8	38.3	32.3	31.2	25.9	22.1	21.6	18.1	15.5
-25		30.9	26.3	23.0	22.3	19.0	16.6	16.3	13.9	12.1
-15		33.1	28.1	24.4	23.7	20.2	17.5	17.3	14.7	12.8
-5	30	37.1	31.1	26.8	26.0	21.9	19.0	18.6	15.8	13.6
5		45.5	37.1	31.3	30.3	25.1	21.4	21.0	17.5	15.0
15		70.1	52.5	37.1	40.1	31.7	26.2	25.6	20.8	17.5
-25		31.1	26.5	23.1	22.5	19.1	16.7	16.4	14.0	12.2
-15		34.0	28.7	24.9	24.2	20.5	17.8	17.5	14.9	12.9
-5	45	39.7	33.0	28.2	27.3	22.8	19.6	19.3	16.2	14.0
5		54.9	43.2	35.5	34.2	27.7	23.2	22.8	18.8	15.9
15		N/A	83.9	59.8	56.1	40.9	32.2	31.3	24.4	20.0
-25		31.4	26.8	23.3	22.6	19.3	16.8	16.5	14.0	12.2
-15		34.9	29.4	25.4	24.6	20.8	18.0	17.7	15.0	13.0
-5	60	42.7	35.0	29.7	28.7	23.8	20.3	20.0	16.7	14.4
5		69.3	51.6	41.0	39.2	30.9	25.5	24.9	20.2	17.0
15		N/A	N/A	N/A	93.7	57.9	41.8	40.4	29.6	23.3
-25		31.7	27.0	23.4	22.8	19.4	16.8	16.6	14.1	12.3
-15		35.8	30.1	25.9	25.1	21.2	18.3	18.0	15.2	13.2
-5	75	46.3	37.4	31.3	30.2	24.9	21.1	20.7	17.2	14.7
5		93.8	64.0	48.6	46.0	35.0	28.2	27.5	21.9	18.1
15		N/A	N/A	N/A	286.4	99.1	59.8	56.9	37.6	28.0

Table 3. Moisture control ventilation rates (m^3 h^{-1} head^{-1}) for typical indoor and outdoor conditions for a farrowing barn. Average sow and litter weight = 175 kg, MP = 2.38 g h^{-1} kg^{-1}, t_i is indoor temperature setting, t_o is outdoor temperature, RH$_i$ is indoor relative humidity setting, and RH$_o$ is outdoor relative humidity.

		t_i = 15°C			t_i = 20°C			t_i = 25°C		
t_o (°C)	RH$_o$ (%)	60% RH$_i$	70% RH$_i$	80% RH$_i$	60% RH$_i$	70% RH$_i$	80% RH$_i$	60% RH$_i$	70% RH$_i$	80% RH$_i$
-25		46.6	39.8	34.7	33.7	28.8	25.1	24.7	21.1	18.4
-15		49.2	41.9	36.5	35.5	30.3	26.4	25.9	22.1	19.3
-5	15	53.0	44.9	39.0	37.8	32.1	27.9	27.5	23.4	20.3
5		59.3	49.7	42.7	41.4	34.9	30.1	29.6	25.0	21.7
15		N/A	N/A	N/A	47.5	39.4	33.6	33.0	27.6	23.7
-25		47.0	40.1	35.0	34.0	29.0	25.3	24.9	21.2	18.5
-15		50.4	42.8	37.2	36.1	30.7	26.7	26.3	22.4	19.5
-5	30	56.5	47.4	40.9	39.6	33.4	28.9	28.4	24.0	20.8
5		69.4	56.6	47.8	46.1	38.2	32.6	31.9	26.7	22.9
15		N/A	N/A	N/A	61.1	48.3	39.9	39.0	31.6	26.6
-25		47.5	40.4	35.2	34.2	29.2	25.4	25.0	21.3	18.5
-15		51.7	43.8	37.9	36.8	31.2	27.1	26.6	22.6	19.7
-5	45	60.5	50.2	42.9	41.5	34.8	29.9	29.4	24.7	21.3
5		83.7	65.8	54.1	52.0	42.2	35.4	34.7	28.6	24.3
15		N/A	N/A	N/A	85.5	62.4	49.0	47.7	37.2	30.4
-25		47.9	40.8	35.5	34.4	29.3	25.5	25.1	21.4	18.6
-15		53.1	44.8	38.7	37.5	31.7	27.5	27.0	22.9	19.8
-5	60	65.1	53.4	45.2	43.7	36.3	31.0	30.4	25.5	21.9
5		105.6	78.6	62.5	59.7	47.1	38.8	37.9	30.8	25.8
15		N/A	N/A	N/A	142.8	88.2	63.7	61.5	45.0	35.5
-25		48.4	41.1	35.7	34.7	29.5	25.7	25.2	21.5	18.7
-15		54.6	45.8	39.4	38.2	32.2	27.9	27.4	23.2	20.0
-5	75	70.5	57.0	47.7	46.0	37.9	32.2	31.5	26.2	22.5
5		142.9	97.6	74.0	70.1	53.3	43.0	41.9	33.3	27.6
15		N/A	N/A	N/A	436.3	151.0	91.1	86.6	57.2	42.6

may result in the growth of microorganisms or structural degradation (Jones et al., 2015).

One outcome of the updated HMP data is that across all stages of production, the magnitude of MP increases is greater than that of SHP increases. This leads to a greater increase in VR for moisture control compared to that for temperature control, which results in elevation of t_{bal}. The concern with this shift in t_{bal} is that the mass of water vapor in the air is possibly greater as the outside temperature approaches t_{bal}. Figure 5 plots t_{bal} for the nursery stage; using recent data, the t_{bal} is determined to be 11°C. However, calculations from the HMP values in ASABE Standard EP270.5 (ASABE, 2012) result in a t_{bal} closer to -15°C. Us-

Table 4. Moisture control ventilation rates (m^3 h^{-1} $head^{-1}$) for typical indoor and outdoor conditions for a wean-to-finish barn. Average pig weight = 16.7 kg (nursery stage), MP = 7.86 g h^{-1} kg^{-1}, t_i is indoor temperature setting, t_o is outdoor temperature, RH_i is indoor relative humidity setting, and RH_o is outdoor relative humidity).

		t_i = 15°C			t_i = 20°C			t_i = 25°C		
t_o (°C)	RH_o (%)	60% RH_i	70% RH_i	80% RH_i	60% RH_i	70% RH_i	80% RH_i	60% RH_i	70% RH_i	80% RH_i
-25		10.6	9.1	7.9	7.8	6.7	5.8	5.8	4.9	4.3
-15		11.2	9.5	8.3	8.2	7.0	6.1	6.0	5.1	4.5
-5	15	11.9	10.1	8.8	8.7	7.4	6.4	6.4	5.4	4.7
5		13.0	11.0	9.5	9.3	7.9	6.8	6.8	5.8	5.0
15		N/A	N/A	N/A	10.4	8.7	7.5	7.4	6.2	5.4
-25		10.7	9.1	8.0	7.8	6.7	5.8	5.8	4.9	4.3
-15		11.4	9.7	8.4	8.3	7.1	6.1	6.1	5.2	4.5
-5	30	12.5	10.5	9.1	8.9	7.6	6.6	6.5	5.5	4.8
5		14.5	12.0	10.3	10.1	8.4	7.2	7.2	6.0	5.2
15		N/A	N/A	N/A	12.3	10.0	8.4	8.3	6.9	5.8
-25		10.8	9.2	8.0	7.9	6.7	5.8	5.8	5.0	4.3
-15		11.6	9.8	8.5	8.4	7.1	6.2	6.2	5.2	4.5
-5	45	13.1	11.0	9.4	9.3	7.8	6.7	6.7	5.6	4.9
5		16.4	13.3	11.2	10.9	9.0	7.6	7.6	6.3	5.4
15		N/A	N/A	N/A	15.0	11.7	9.6	9.5	7.6	6.4
-25		10.9	9.2	8.0	7.9	6.7	5.9	5.8	5.0	4.3
-15		11.8	10.0	8.7	8.5	7.2	6.3	6.2	5.3	4.6
-5	60	13.8	11.4	9.8	9.6	8.0	6.9	6.9	5.8	5.0
5		18.8	14.8	12.2	12.0	9.7	8.1	8.1	6.7	5.6
15		N/A	N/A	N/A	19.4	14.2	11.2	11.1	8.6	7.1
-25		10.9	9.3	8.1	8.0	6.8	5.9	5.9	5.0	4.3
-15		12.0	10.2	8.8	8.6	7.3	6.3	6.3	5.3	4.6
-5	75	14.5	11.9	10.1	9.9	8.3	7.1	7.0	5.9	5.1
5		22.1	16.8	13.5	13.2	10.5	8.7	8.6	7.0	5.9
15		N/A	N/A	N/A	27.3	18.0	13.4	13.3	9.9	7.9

Table 5. Moisture control ventilation rates (m^3 h^{-1} $head^{-1}$) for typical indoor and outdoor conditions for a wean-to-finish barn. Average pig weight = 34.1 kg (growing stage), MP = 2.85 g h^{-1} kg^{-1}, t_i is indoor temperature setting, t_o is outdoor temperature, RH_i is indoor relative humidity setting, and RH_o is outdoor relative humidity.

		t_i = 15°C			t_i = 20°C			t_i = 25°C		
t_o (°C)	RH_o (%)	60% RH_i	70% RH_i	80% RH_i	60% RH_i	70% RH_i	80% RH_i	60% RH_i	70% RH_i	80% RH_i
-25		10.9	9.3	8.1	7.9	6.7	5.9	5.8	4.9	4.3
-15		11.5	9.8	8.5	8.3	7.1	6.2	6.1	5.2	4.5
-5	15	12.4	10.5	9.1	8.8	7.5	6.5	6.4	5.4	4.7
5		13.8	11.6	10.0	9.7	8.1	7.0	6.9	5.8	5.1
15		N/A	N/A	N/A	11.1	9.2	7.8	7.7	6.4	5.5
-25		11.0	9.4	8.2	7.9	6.8	5.9	5.8	4.9	4.3
-15		11.8	10.0	8.7	8.4	7.2	6.2	6.1	5.2	4.5
-5	30	13.2	11.1	9.5	9.2	7.8	6.7	6.6	5.6	4.9
5		16.2	13.2	11.1	10.8	8.9	7.6	7.5	6.2	5.3
15		N/A	N/A	N/A	14.2	11.3	9.3	9.1	7.4	6.2
-25		11.1	9.4	8.2	8.0	6.8	5.9	5.8	5.0	4.3
-15		12.1	10.2	8.9	8.6	7.3	6.3	6.2	5.3	4.6
-5	45	14.1	11.7	10.0	9.7	8.1	7.0	6.9	5.8	5.0
5		19.5	15.4	12.6	12.1	9.8	8.3	8.1	6.7	5.7
15		N/A	N/A	N/A	20.0	14.6	11.4	11.1	8.7	7.1
-25		11.2	9.5	8.3	8.0	6.8	6.0	5.9	5.0	4.3
-15		12.4	10.4	9.0	8.8	7.4	6.4	6.3	5.3	4.6
-5	60	15.2	12.5	10.5	10.2	8.5	7.2	7.1	5.9	5.1
5		24.6	18.3	14.6	13.9	11.0	9.1	8.9	7.2	6.0
15		N/A	N/A	N/A	33.3	20.6	14.9	14.3	10.5	8.3
-25		11.3	9.6	8.3	8.1	6.9	6.0	11.3	9.6	8.3
-15		12.7	10.7	9.2	8.9	7.5	6.5	12.7	10.7	9.2
-5	75	16.5	13.3	11.1	10.7	8.8	7.5	16.5	13.3	11.1
5		33.3	22.8	17.3	16.4	12.4	10.0	33.3	22.8	17.3
15		N/A	N/A	N/A	101.8	35.2	21.3	-49.6	148.6	148.3

ing an example of the 99% design temperature of the central Illinois region, which is -15.1°C (ASHRAE, 2013), and 45% for RH_o, the data in table 4 can be used to evaluate the ventilation required as the temperature approaches specific indoor set points. Given indoor set points of 25°C and 70% RH_i, the corresponding VR based on the assumption above is 5.2 m^3 h^{-1} $head^{-1}$ (table 4). As the outdoor temperature approaches t_{bal} at 5°C and 45% RH, for the same indoor condition (25°C and 70%), VR climbs to 6.3 m^3 h^{-1} $head^{-1}$ (table 4). Even if the indoor conditions allowed for 80% RH at 25°C, the V_{H2O} required is still greater than the initial design (5.4 vs. 5.2 m^3 h^{-1} $head^{-1}$). While the RH_o is not increased, the water vapor does increase and results in elevation of RH_i. When the outdoor temperature is below or equal

Table 6. Moisture control ventilation rates ($m^3 h^{-1} head^{-1}$) for typical indoor and outdoor conditions for a wean-to-finish barn. Average pig weight = 117.7 kg (finishing stage), MP = 1.2 $g h^{-1} kg^{-1}$, t_i is indoor temperature setting, t_o is outdoor temperature, RH_i is indoor relative humidity setting, and RH_o is outdoor relative humidity.

		t_i = 15°C			t_i = 20°C			t_i = 25°C		
t_o (°C)	RH_o (%)	60% RH_i	70% RH_i	80% RH_i	60% RH_i	70% RH_i	80% RH_i	60% RH_i	70% RH_i	80% RH_i
-25		15.8	13.5	11.8	11.4	9.8	8.5	8.4	7.2	6.2
-15		16.7	14.2	12.4	12.0	10.3	8.9	8.8	7.5	6.5
-5	15	18.0	15.2	13.2	12.8	10.9	9.5	9.3	7.9	6.9
5		20.1	16.8	14.5	14.0	11.8	10.2	10.0	8.5	7.3
15		N/A	N/A	N/A	16.1	13.4	11.4	11.2	9.3	8.0
-25		15.9	13.6	11.9	11.5	9.8	8.6	8.4	7.2	6.3
-15		17.1	14.5	12.6	12.3	10.4	9.1	8.9	7.6	6.6
-5	30	19.2	16.1	13.9	13.4	11.3	9.8	9.6	8.1	7.1
5		23.5	19.2	16.2	15.6	12.9	11.0	10.8	9.0	7.8
15		N/A	N/A	N/A	20.7	16.4	13.5	13.2	10.7	9.0
-25		16.1	13.7	11.9	11.6	9.9	8.6	8.5	7.2	6.3
-15		17.5	14.8	12.9	12.5	10.6	9.2	9.0	7.7	6.7
-5	45	20.5	17.0	14.6	14.1	11.8	10.1	10.0	8.4	7.2
5		28.4	22.3	18.4	17.6	14.3	12.0	11.8	9.7	8.2
15		N/A	N/A	N/A	29.0	21.1	16.6	16.2	12.6	10.3
-25		16.2	13.8	12.0	11.7	9.9	8.7	8.5	7.3	6.3
-15		18.0	15.2	13.1	12.7	10.8	9.3	9.2	7.8	6.7
-5	60	22.1	18.1	15.3	14.8	12.3	10.5	10.3	8.6	7.4
5		35.8	26.6	21.2	20.3	16.0	13.2	12.9	10.4	8.8
15		N/A	N/A	N/A	48.4	29.9	21.6	20.9	15.3	12.0
-25		16.4	13.9	12.1	11.8	10.0	8.7	8.6	7.3	6.3
-15		18.5	15.5	13.4	13.0	10.9	9.4	9.3	7.9	6.8
-5	75	23.9	19.3	16.2	15.6	12.8	10.9	10.7	8.9	7.6
5		48.5	33.1	25.1	23.8	18.1	14.6	14.2	11.3	9.4
15		N/A	N/A	N/A	148.0	51.2	30.9	29.4	19.4	14.5

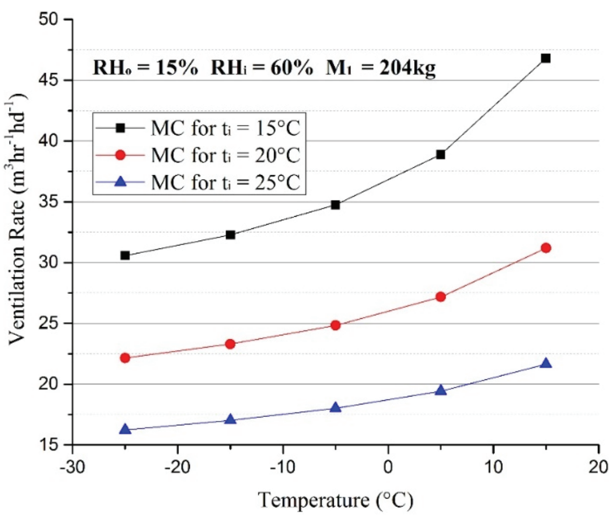

Figure 1. Minimum ventilation rates for moisture control (MC) required for the gestation stage for three indoor set point temperatures. M_1 is mass of sows in the gestation stage, t_i is indoor temperature, RH_i is indoor relative humidity, and RH_o is outdoor relative humidity.

to t_{bal}, the VR is expected to remain constant at a level for moisture control. When outdoor conditions approach t_{bal}, if the outside humidity does not fall with the increasing air temperature and/or the initial design RH_i is not conservative, then the VR for moisture control at design conditions may not be adequate. The higher t_{bal} will include more days of minimum VR when these conditions could occur. Determining set point temperature for the first stage of VR should consider local design temperature, the corresponding relative humidity change, and balance temperature. In more humid environments and production stages that have large differences between t_o and t_{bal}, it would likely be advantageous to design for a lower RH_i condition.

Figure 2a shows the effects of single-stocking versus double-stocking on V_{temp} for temperature control (RH_o = 15% and t_i = 15°C). Weaned pigs were double-stocked when they entered the wean-to-finish barn. As they continued growing, half of the pigs were moved to a second room while the rest of pigs remained in the room, which was then described as single-stocked. As the graph shows, V_{temp} for a single-stocked barn is higher than V_{temp} for a double-stocked barn, which is due to the greater total mass of the finishing pigs in single-stocked housing. The total weight of the animals has a dominant effect on V_{temp} that causes the finishing stage to have a higher design V_{temp}. To include proper fan capacity, V_{temp} for the finishing stage instead of the growing stage should be the VR design criterion for the barn. Figure 2b shows VR in $m^3 h^{-1} kg^{-1}$; without the effect of total animal mass, both V_{temp} and V_{H2O} (RH_i = 60% and RH_i = 80%) are higher for the growing stage than for the finishing stage, resulting from higher specific SHP and MP for the growing stage (2.29 W kg^{-1} and 2.85 g h^{-1} kg^{-1}, respectively) compared to the finishing stage (1.27 W kg^{-1} and 1.2 g h^{-1} kg^{-1}, respectively). The t_{bal} for the finishing and growing stages is -28°C and -15°C, respectively, at RH_o = 50%. In the winter, supplemental heating was used until the barn reached t_{bal}. Because nursery, growing, and finishing pigs are all reared in the same barn, it is necessary to have the ventilation capacity and supplemental heating required for all stages. The ability to control minimum VR based on animal weight and barn stocking rate would provide opportunities to optimize fuel use.

Figures 3 through 7 show typical V_{H2O} values versus outside temperature by production stage for both moisture and temperature control. The ventilation rates calculated based

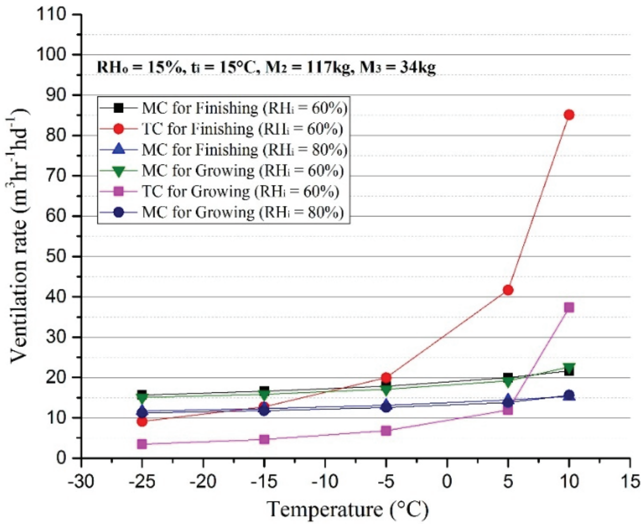

Figure 2a. Typical ventilation rates (m^3 h^{-1} head^{-1}) for moisture control (MC) and temperature control (TC) for single-stocked (finishing) and double-stocked (growing) stages in a grow-to-finish barn. MC is based on two indoor RH set points (60% and 80%). M_2 is mass of pigs in the finishing stage, M_3 is mass of pigs in the growing stage, t_i is indoor temperature, RH$_i$ is indoor relative humidity, and RH$_o$ is outdoor relative humidity.

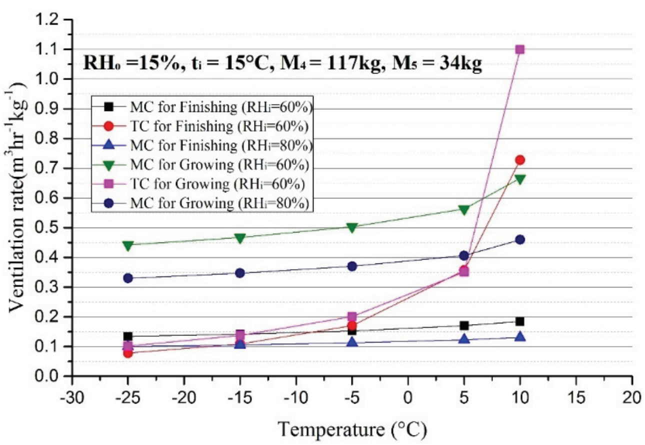

Figure 2b. Typical ventilation rates (m^3 h^{-1} kg^{-1}) for moisture control (MC) and temperature control (TC) for single-stocked (finishing) and double-stocked (growing) stages in a grow-to-finish barn. MC is based on two indoor RH set points (60% and 80%). M_4 is mass of pigs in the finishing stage, M_5 is mass of pigs in the growing stage, t_i is indoor temperature, RH$_i$ is indoor relative humidity, and RH$_o$ is outdoor relative humidity.

on the new and old HMP values are compared in these graphs. In general, increasing outside temperature elevates VR across all five stages, and VR for temperature control increases faster than VR for moisture control under the same environmental conditions. Overall, the ventilation rates from the new HMP values are higher than the ventilation rates from the old HMP values in ASABE Standard EP270.5 (ASABE, 2012) across all five stages. The t_{bal} based on new HMP for the gestation, farrowing, nursery, growing, and finishing stages are -5°C, -4°C, 11°C, -5°C, and -28°C, respectively. These t_{bal} values suggest a need for supplemental heating for barns in many regions.

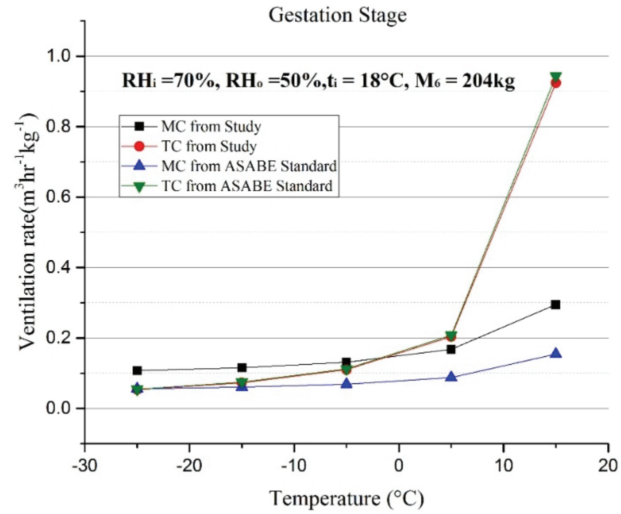

Figure 3. Typical ventilation rates for moisture control (MC) and temperature control (TC) for the gestation stage. M_6 is mass of pigs in the gestation stage, t_i is indoor temperature, RH$_i$ is indoor relative humidity, and RH$_o$ is outdoor relative humidity.

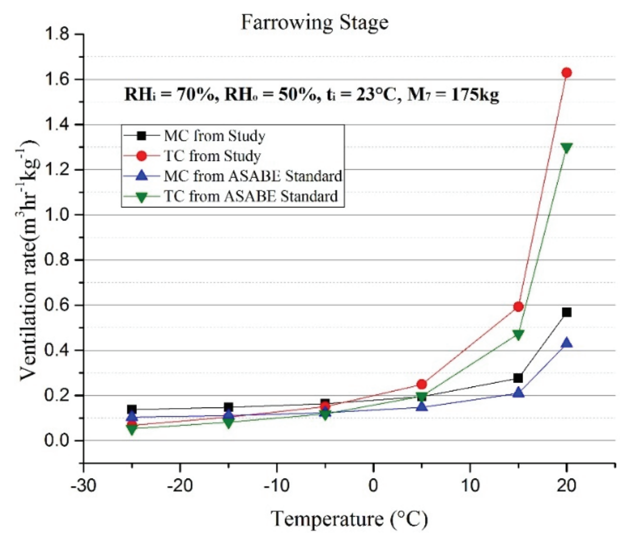

Figure 4. Typical ventilation rates for moisture control (MC) and temperature control (TC) for the farrowing stage. M_7 is mass of sows in the farrowing stage, t_i is indoor temperature, RH$_i$ is indoor relative humidity, and RH$_o$ is outdoor relative humidity.

Ventilation rates from Zhang (1994) and MWPS (1990) were compared with the new VRs. The V_{H2O} values recommended by Zhang (1994) were 54%, 30%, 69%, 31%, and 53% lower than the new V_{H2O} values for the gestation, farrowing, nursery, growing, and finishing stages, respectively, which is due to the higher LHP or MP of the animals plus inclusion of MP from the surroundings. In these comparisons, the same outdoor temperature of -25°C was used, providing minimum VRs for extreme winter conditions for many regions. For example, in the farrowing stage (175 kg), the new MP (2.38 g h^{-1} kg^{-1}) is 78% higher than the old MP (1.34 g h^{-1} kg^{-1}) for a given room temperature, leading to a 30% increase in V_{H2O}. Compared to the VRs recommended by MWPS (1990), the old VRs were 40%, 34%, 56%, 2%, and 3% lower than the new VRs for the gestation, farrowing,

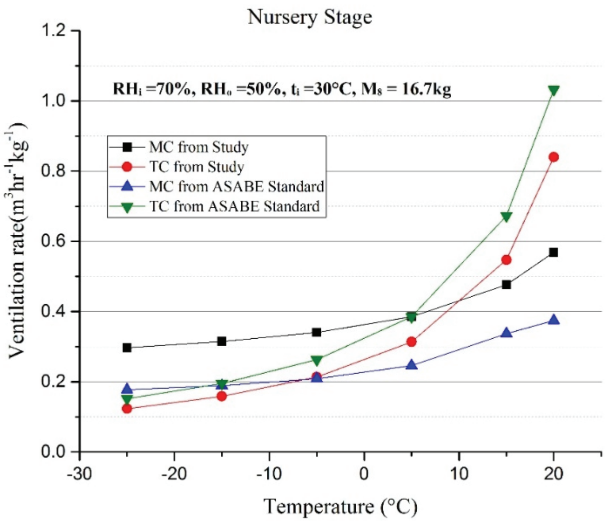

Figure 5. Typical ventilation rates for moisture control (MC) and temperature control (TC) for the nursery stage. M_8 is mass of pigs in the nursery stage, t_i is indoor temperature, RH_i is indoor relative humidity, and RH_o is outdoor relative humidity.

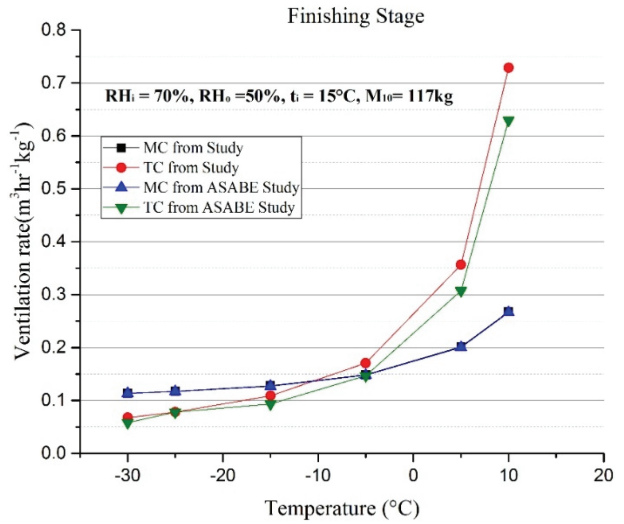

Figure 7. Typical ventilation rates for moisture control (MC) and temperature control (TC) for the finishing stage. M_{10} is mass of pigs in the finishing stage, t_i is indoor temperature, RH_i is indoor relative humidity, and RH_o is outdoor relative humidity.

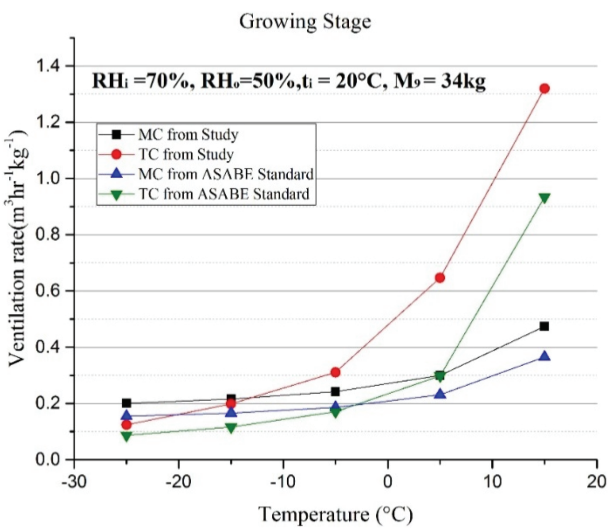

Figure 6. Typical ventilation rates for moisture control (MC) and temperature control (TC) for the growing stage. M_9 is mass of pigs in the growing stage, t_i is indoor temperature, RH_i is indoor relative humidity, and RH_o is outdoor relative humidity.

nursery, growing, and finishing stages, respectively. It is important to note that for the winter conditions used in the comparison with MWPS, the finishing stage minimum VR was controlled by V_{temp} for many locations due to low t_{bal} (-28°C), while the remaining stages were managed for V_{H2O}. In comparison with both sets of recommendations, the VR increases were highest in the gestation and nursery stages. This agreed with the greatest increase in LHP shown in table 1. The increase in LHP or MP is largest in the nursery stage as determined from the HMP data, which may need further investigation. Some of this high facility-level MP may be due to the undeveloped urination and defecation patterns of the piglets on partially slatted floors, leading to increased washing or higher than average evaporation of urine (Brown-Brandl et al., 2014). It may also be typical of commercial barns. Further validation of these data would be valuable prior to increasing V_{H2O} for the nursery stage.

The VRs discussed in these cases were based on sensible heat and moisture balance by modeling. The results can be validated by experimental studies. Samer et al. (2011, 2012) attempted to quantify the VR of a naturally ventilated building using a mass balance approach, including moisture balance, CO_2 balance, heat balance, and a tracer gas technique. The tracer gas technique was found to be the most reliable method of VR measurement for both summer and winter seasons and might be used for validating the VRs calculated in this study. However, the method was validated only in a naturally ventilated animal house. Modification of the method might be expected before application in a mechanically ventilated barn.

Conclusion

This article demonstrates why updating the VR recommendations is needed. The swine production stages evaluated in this study included gestation, farrowing, nursery, growing, and finishing. Overall, previous VR recommendations or VR values based on old HMP values substantially underestimate the need for both moisture and temperature control. The results showed that the old VRs for moisture control were 54%, 30%, 69%, 31%, and 53% lower than the new VRs in the gestation, farrowing, nursery, growing, and finishing stages, respectively.

In addition, t_{bal} for gestation, farrowing, nursery, growing, and finishing for typical housing for assumed indoor and outdoor environmental conditions in the Midwestern U.S. are -5°C, -4°C, 11°C, -5°C, and -28°C, respectively. These t_{bal} values suggest a need for supplemental heating in barns, especially during the early (nursery) stage in wean-to-finish barns. The t_{bal} should be considered for designing the first stage of VR in order to provide adequate supplemental heating.

This study provides usable lookup tables of VR for moisture control based on indoor and outdoor conditions. The tables provide a useful tool for evaluating V_{H2O} based on local conditions. Because the design of swine barns varies from region to region, VRs based on the new HMP rates for different types and scales of swine barns warrant further work.

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